APPENDIX D

POPULATION VIABILITY ANALYSIS FOR PACIFIC COAST SNOWY PLOVERS

Nadav Nur
Gary W. Page
Lynne E. Stenzel

Point Reyes Bird Observatory
4990 Shoreline Highway
Stinson Beach, CA 94970

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e-mail: nadavnur@prbo.org
gpage@prbo.org
lstenzel@prbo.org

Acknowledgments

Introduction

In 1993 the Pacific coast population of the snowy plover (*Charadrius alexandrinus nivosus*) was designated as threatened by the U.S. Fish and Wildlife Service under the Endangered Species Act. To aid the Snowy Plover Recovery Team in developing recovery criteria, the authors developed this population viability analysis for Pacific coast snowy plovers.

Population viability analysis is used increasingly as a tool for developing conservation, management or restoration strategies for threatened, endangered, or potentially threatened species. The method is reviewed by Boyce (1992), Burgman *et al*. (1993), Beissinger and Westphal (1998) and Nur and Sydeman (1999). Examples of its use include Haig *et al*. (1993), Maguire *et al*. (1995), Akçakaya *et al*. (1995), and Bustamante (1996). In particular, population viability analyses have been developed for the congener piping plover *Charadrius melodus* (Great Plains population: Ryan 1993; Atlantic coast population: Melvin and Gibbs 1996).

General Features of the Population Viability Analysis Model
The model is stochastic. Stochasticity is one of the defining features of Population Viability Analyses in general (Burgman *et al*. 1993). Two types of random variation are incorporated: unpredictable variation in the environment and "demographic stochasticity." Demographic stochasticity can be thought of as follows: even if all relevant features of the environment (including predators, competitors, abiotic factors, etc.) impinging on snowy plovers are known, and even though, on average, survival or reproductive success can be related to these environmental features, there will still be an element of unpredictability regarding the precise number of young or adults that survive or the number of fledglings produced in any time period.

For the population viability analysis, we have used a metapopulation model with six subpopulations linked by dispersal of individuals. A metapopulation is a set of subpopulations among which there is restricted dispersal (Harrison 1994, Nur and Sydeman *in press*). In this population viability analysis, we have incorporated into the metapopulation model the best available estimates on dispersal. However, using the same model structure, one can easily alter the parameter values of dispersal, and, indeed, we do so. An alternative approach would be to treat Pacific coast birds as a single population, with unrestricted mating among all individuals, regardless of location. The latter model assumes that a bird from, say, Oregon is as likely to mate with a bird from San Diego as with a bird from Oregon. Such an assumption is exceedingly unrealistic; hence, we have adopted a metapopulation model. Another virtue of the metapopulation approach is that survival and/or fecundity can be allowed to vary among subpopulations, rather than being assumed homogeneous throughout the species' range. Note that the Atlantic coast piping plover population viability analysis assumed a single, panmictic population instead of a metapopulation (U.S. Fish and Wildlife Service 1996).

The population viability analysis is carried out using the RAMAS/GIS program which is commercially available (Akçakaya 1997) and has been widely used for population viability

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analyses. Use of an off-the-shelf program makes modeling convenient and reproducible, but there are attendant limitations regarding input and output. For example, RAMAS/GIS allows one to specify the degree of stochastic variability in survival and reproductive success, but not dispersal. Other limitations are mentioned in the "Discussion." The Snowy Plover Recovery Team determined that the cost of developing a specially written program to carry out the population viability analysis was not justified.

The type of model that can be generated using RAMAS/GIS does not incorporate the production and elimination of genetic variation brought about by sexual reproduction (Caswell 1989, Beissinger and Westphal 1998). As a simplification, only one sex is modeled. We have used males because their demographic parameters can be estimated with greater certainty than for females. In addition, there is reason to consider that the availability of males is limiting reproductive success because they are responsible for post-hatching parental care and females can lay clutches for more than one male (Warriner *et al*. 1986).

The snowy plover population viability analysis projects into the future up to 100 years. Although, there is considerable uncertainty in projecting 100 years, this time-horizon is commonly used and is recommended by Mace and Lande (1991). This time horizon was also used for the Atlantic coast Piping Plover Recovery Plan. We also depict population trajectories for shorter time-horizons.

The population viability analysis indicates trends and quantifies the risk that the total population goes extinct or falls below a **specified threshold**. We used a specified threshold of 50 individuals, but the population viability analysis could be modified by choosing any other threshold value.

The population viability analysis includes different scenarios pertaining to changes in reproductive success resulting from predator management and could be used to model other changes in management practices or the environment, affecting any of the other demographic parameters.

Subpopulations
The Snowy Plover Recovery Team has identified six subpopulations of snowy plovers, each corresponding to a region of the U S. Pacific coast. The population viability analysis assumes restricted dispersal among subpopulations, but unrestricted access to mates within

subpopulations. The six subpopulations, with their two-letter or three-letter designations, and estimated population sizes are:

1. Oregon and Washington coast (OR) estimated at 134 plovers;
2. Northern California coast (NC; Del Norte, Humboldt and Mendocino counties) with 50 plovers;
3. San Francisco Bay (SFB; primarily South Bay) with 264 plovers;
4. Monterey Bay (MB; coast of Sonoma, Marin, San Mateo, Santa Cruz and Monterey counties) with 300 plovers;
5. coast of San Luis Obispo, Santa Barbara and Ventura counties (SLO) with 886 plovers;
6. San Diego area (SD; Los Angeles, Orange and San Diego counties) with 316 plovers.

For the OR, MB, and SD subpopulations, intensive monitoring of color-banded individuals was carried out in 1997, and population size was estimated on that basis. For the NC, SFB and SLO subpopulations, information is less complete. Instead, we relied on "window surveys" conducted in 1995, 1991, and 1995, respectively. To account for birds missed during the window surveys we applied a correction factor to the survey numbers for the NC, SFB and SLO subpopulations. Where window surveys were conducted at locations with color banded birds, the number of marked birds known to be at the location was underestimated by about 22 percent. This takes into account both birds known to be present but missed and birds that were double counted. The correction factor used is $1/(1-.222) = 1.286$. For the NC and SLO subpopulations, the correction factor was applied to the number of birds counted on window surveys in 1995.

However, for the SFB subpopulation, no window survey has been carried out since 1991. Uncertainty about population trends since 1991 compounds uncertainty about current abundance. We therefore considered there to be an upper bound of 310 individuals (219 individuals observed on the window survey in 1991 x 1.286 x 1.1, to account for modest population growth since 1991) and a lower bound of 219 individuals (population decline since 1991, equal in magnitude to the undercounting during the window survey). For modeling, we used the mean of those two estimates (= 264 individuals).

Conceptual Framework of the Model
The key demographic parameters in the model are: (1) adult survival, (2) juvenile survival, (3) reproductive success, and (4) dispersal. All individuals 1 year or older are considered to be adult, and assumed to breed (see below). The demographic parameters are linked in the population

model in the following manner, ignoring dispersal among subpopulations (detailed later) and ignoring any stochastic effects.

The model keeps track of the abundance of each age class (one-year-old, two-year-old, etc., up to twenty-year-old individuals) in each subpopulation. This enumeration by the model is carried out at the onset of the breeding season; this is referred to as a pre-breeding census. In the model, the number of two-year-olds in year t+1, symbolized $N(2)_{t+1}$ is equal to the number of one-year-olds in year t, symbolized $N(1)_t$, times the annual survival rate of one-year-olds, symbolized S_1. Note that S_1 is not constant, but varies stochastically from year to year, and differs among subpopulations. Similar calculations are performed for the number of three-year-olds, i.e., $N(3)_{t+1} = N(2)_t*S_2$, four-year-olds, etc. In the model, adult survival is assumed to be the same for all ages, i.e., $S_1 = S_2 = ... = S_{19}$, but no adult lives beyond 20 years of age, which is considered maximum age for this species.

The number of one-year-olds in a given year is equal to the number of fledged chicks produced the year before times the probability that a fledged chick will survive to reach the age of one year. If the total number of adults the year before is written $N(A)_t = N(1)_t + N(2)_t + ... + N(20)_t$, then the number of one-year-olds in year t+1, symbolized $N(1)_{t+1}$, is equal to the product $N(A)_t*F*S_0$, where F is the number of male fledglings produced per male adult in each year, and S_0 is the probability a fledgling survives to one year (12 months) of age. Since the sex ratio of fledglings is unknown, we assume a 1:1 ratio. Any non-breeding among adults would act to reduce F; however, all adults are assumed to breed (see below). In the model, F and S_0 also vary among subpopulations and vary randomly among years, with a specified mean and standard deviation.

Parameter Estimates
Adult survival - The best estimates for adult survival came from capture/recapture analyses of Monterey Bay color-banded plovers, a major study population (henceforth Monterey Bay) situated within the MB subpopulation. Additional data for analyses came from color-banded study populations on Oregon beaches (Oregon) and San Diego beaches (San Diego). Note that we distinguish between study areas (Monterey Bay, Oregon and San Diego) and their respective, more inclusive subpopulations (MB, OR, SD). Analyses of survival were carried out using the program SURGE (Lebreton *et al*. 1992, Cooch *et al*. 1996) and for Monterey Bay were based on 777 adults (361 males, 416 females) followed over 14 years. Sample sizes for Oregon were 108 males and 70 females, followed over 8 years, and for San Diego 91 males and 137 females, followed over 4 years. Since male survival significantly exceeded female survival at Monterey

Bay and only males were modeled, we present only estimates for male adults, for the Monterey Bay, Oregon and San Diego study populations.

We fit a two-age class model for male adult survival, in which the first age class covers the first year after first capture, and the second age class covers all subsequent years. Estimates of survival for the first age class can be biased due to behavioral responses to trapping and banding, lower site-fidelity among some first-time captures, and other methodological difficulties. These biases do not apply to survival after the first year of banding (Pradel *et al*. 1997). For this reason, several studies have used only survival estimates from the second age class (e.g., Gaston 1992, Johnston *et al*. 1997); we adopted the same practice.

A potential shortcoming of capture/recapture analyses of survival is that they cannot allow for permanent emigration, though they can allow for temporary emigration (Lebreton *et al*. 1992). A bird which moves permanently out of the study area cannot be distinguished from one that has died. The problem of permanent emigration can be overcome somewhat by enlarging the study area. In our analyses we compare survival estimates from three nested data sets, which differ only in the spatial and temporal extent of resightings. The most restricted data set included only resightings from birds seen during the breeding season in the same study area. In the next, more comprehensive data set, resightings of color-banded birds at other study areas were also included. In the most extensive data set, resightings during the entire year were included, as well as resightings at other study areas. The extent to which survival estimates differ among the three data sets provides insight into the magnitude of the problem of dispersal (permanent emigration).

Male survival estimates for Monterey Bay, for 2nd-year and older adults, were 74, 74, and 75 percent for the three data sets (Table D-1A). In other words, survival estimates differed slightly depending on the spatial extent of coverage and whether winter observations were included. Increasing the study area for Monterey Bay birds (either spatially or through observations outside the breeding season), increased the survival estimates by up to 1 percent. This implies that 1 percent of the individuals, inferred to be dead if observations are only from one study area and only during the breeding season, are inferred to be alive using the data from the enlarged study area. These results suggest that amount of dispersal out of the original study area is not negligible but it is also not great. Since not all breeding areas of Pacific coast snowy plovers are adequately surveyed for color-banded birds, we assume that there was additional, **undetected** dispersal out of the study area on the order of 1 percent. If so, then the true adult survival rate is 76 percent.

For the Oregon study population, male survival values were 74 to 75 percent, i.e., nearly identical to those from Monterey Bay (Table D-1A). Estimates for San Diego are somewhat lower, at 71 percent, but the difference between the San Diego estimates and those from Monterey Bay is no greater than the standard error of these estimates (Table D-1A). Among all three sites, survival estimates did not differ to a statistically significant degree. In the population viability analysis, we assume a survival rate of 76 percent for all subpopulations, but also model population trajectories with an adult survival of 75 percent and 77 percent, for all subpopulations. Capture/recapture analyses of Atlantic coast piping plovers resulted in a survival estimate of 74 percent (Melvin and Gibbs 1996). Paton (1994) analyzed survival for Great Salt Lake snowy plovers over a 3-year period. Survival rates were pooled over the two sexes (unlike our analyses), and differed among years, ranging from 58 percent to 88 percent, with median survival = 73 percent. Thus, survival values from other plover studies are consistent with the survival values used here.

Finally, the year to year variation in male survival for Monterey Bay was estimated to be 5.65 percent (standard deviation). We used this parameter value in our simulations, for all six subpopulations. Note that "catastrophic mortality" (see below), represents additional temporal variation.

Juvenile survival - Table D-1B shows survival estimates for first year birds (from fledging to 12 months of age), by study population and data set. Sample sizes were 1069 fledged young at Monterey Bay, 207 at Oregon and 102 at San Diego. Results were very similar at Monterey Bay and San Diego; Oregon values were somewhat higher but not statistically divergent from Monterey Bay. We therefore used juvenile survival estimates for Monterey Bay for all subpopulations. The different estimates for Monterey Bay, depending on the data set, were 39 percent, 44 percent and 45 percent. Note that for Monterey Bay as we expand the data from just 1 study site to a large network of sites, the survival estimate increases by 5 to 6 percent in absolute terms, and by 15 percent in relative terms. Compare this to the increase in adult survival estimates by 1 percent for the same series of nested data sets (see above). Thus, it is clear that there is quite a bit of dispersal among first-year birds. Undoubtedly, we are still underestimating survival because of permanent emigration. Therefore, we increased the survival estimate to 50 percent. This would imply that among 100 fledged young, 50 survive to age 1, but of these only 39 are inferred to survive based on observations at the single study population, with 11 out of 50 surviving juveniles (or 22 percent) dispersing out of the single study population. This estimate of dispersal is consistent with that directly observed and included in the population viability

analysis (see below). Annual variation in juvenile survival (obtained from Monterey Bay) is also shown in Table D-1B.

Reproductive Success - Here we had empirical data for three study areas, corresponding to three subpopulations (Table D-1C). For Monterey Bay, reproductive success was 0.849 fledged young reared per breeding male in years without predator control and without any exclosures, versus 1.105 fledged young per male in years with predator control and with exclosures. Reproductive success was similar but slightly lower (= 1.04 chicks per male) in Oregon, where intensive management has occurred in all years for which we had data; estimates for Oregon and Monterey Bay are not statistically significantly different for years in which predators were managed. Reproductive success at the San Diego study area, where some (indirect) management activities are thought to have some protective effect on breeding snowy plovers, is a little more than that observed at Monterey Bay without any management activity, but substantially, and significantly, lower than that observed at Monterey Bay and Oregon with management activity.

Simulations assuming that protective management continues in MB and OR, used the respective, current reproductive success values of 1.105 and 1.04 fledglings per male. For SD we did not use the observed reproductive success of 0.917 chicks per male, because this would have produced a subpopulation that (in the absence of net immigration) would have declined at 1.8 percent per year. Such a decline would have been inconsistent with observations and window surveys, which indicate a relatively stable or perhaps increasing SD subpopulation since 1995. Therefore, for the SD subpopulation, we assume that with current management practices continuing, reproductive success is 0.988 chicks per male, a value that produces a numerically stable subpopulation in the long-term (given the other demographic parameter estimates and assumptions). Reproductive success estimates for San Diego were based on only three years of data, and the overall mean of 0.917 may have underestimated the long-term, expected reproductive success.

In the scenarios below we use Monterey Bay past reproductive success (in the absence of intervention) for NC and SFB; i.e., we use that as a best estimate for reproductive success in the absence of predator control/exclosures. We also assume that if management activities cease in MB, OR, and SD regions then reproductive success will be at 0.849 fledged young per male, as well.

For the SLO subpopulation there was considerable uncertainty regarding the appropriate reproductive success value to use. Window surveys indicate that snowy plover numbers have fluctuated over time, with no clear trend discernible, except that, whatever the trend, it is not increasing. At best, the SLO subpopulation might be considered stable; at worst the subpopulation is declining. On that basis, we considered there to be an "optimistic" and a "pessimistic" reproductive success value. The optimistic value is that level of reproductive success which would produce a stable, self-sustaining population (given all other assumptions); that value is 0.988 (the same value used for the SD subpopulation). The pessimistic value is 0.849 chicks per male, the same as used for NC and SFB subpopulations. A third possibility is to use an intermediate value (the mean of the optimistic and pessimistic values = 0.919 chicks per male). In our simulations, we consider all three possibilities, to demonstrate the sensitivity of model results to assumptions about SLO reproductive success. However, in all but two series of simulations, we use the intermediate reproductive success value of 0.919 fledged chicks per male, which in the long-term (given other parameter estimates and assumptions) would produce a population decline of 1.8 percent per year.

For annual variation in reproductive success we used a value of 0.157 (standard deviation.), which is the variation observed in reproductive success at Monterey Bay from 1992-1997. We also note that annual variation in reproductive success among the 3 sites showed weak but not significant correlations. In the scenarios below we assume that all demographic parameters show weak positive correlations ($r = + 0.10$ between pairs of subpopulations).

RAMAS/METAPOP allows one to add "catastrophic mortality" over and above "regular mortality." Catastrophic mortality can include both reproductive failure and changes in survival of juveniles and adults. It is not clear that snowy plovers suffer from catastrophic mortality (none was apparent in the data sets analyzed), yet we should not rule it out. On the basis of recommendations of the Snowy Plover Recovery Team our simulations include additional mortality due to reproductive failure (see below). We also compare simulations with and without this additional catastrophic mortality.

Dispersal - There are qualitative data indicating dispersal, especially of first-year birds, to/from all three intensively studied areas (Monterey Bay, Oregon, and San Diego). The only extensive quantitative data are from Monterey Bay. These data indicated that 21 percent of individuals hatched in Monterey Bay and later observed breeding, were known to breed in areas other than at Monterey Bay. Results from the SURGE analyses of juvenile survival implied a similar

dispersal rate of 22 percent among surviving juveniles (see above). Individuals observed dispersing were seen as far north as Washington and Oregon, and as far south as SLO, but none in the sample were observed going to SD. However, there have been additional observations of Monterey Bay individuals dispersing to SD. Meanwhile, dispersal from SD (43 individuals born at San Diego), indicated a small percentage going to SLO. Using these results, we assumed the following: a general dispersal rate of 25 percent for first-year males; adult males are assumed not to disperse. In other words, we assumed that the total number of birds dispersing exceeded the number known to have dispersed; i.e., some birds dispersed but were undetected. The exception to these assumed dispersal rates was for the most northern subpopulation (OR, which includes Washington) and the most southern, SD. For these, dispersal rates were assumed to be 20 percent, allowing for reduced dispersal from subpopulations, located on the edge of the metapopulation.

We also assumed dispersal was constant, in the absence of information to the contrary. Thus, dispersal did not increase or decrease as subpopulation size increased or decreased. There is little information on dispersal rates in relation to population characteristics for other, similar species (Nur and Sydeman *in press*). For example, a study of Roseate Terns (*Sterna dougallii*; Spendelow *et al*. 1995) found no relationship of dispersal rates to colony size (either colony of origin or colony of destination). RAMAS/GIS does not allow for stochastic variation in dispersal rates among years. Note also, that the metapopulation model does not include dispersal to or from Baja California. This is equivalent to assuming that the number of immigrants from Baja California to the metapopulation equals the number of emigrants dispersing to Baja California. This assumption of balanced dispersal to and from Baja California may be unrealistic, but we had no data on which to develop a metapopulation model which incorporates Baja California.

To demonstrate the impact of a change (or uncertainty) in dispersal rates, we also carry out simulations in which dispersal rates are reduced by 50 percent and by 100 percent.

Additional Assumptions
Density Dependence - Not much is known about this, for any bird species. Following input from Snowy Plover Recovery Team members, we assume a limit on availability of beach habitat, i.e., that there is a region-specific limit on adequate nesting sites. Based on information provided by the recovery team, we estimate the limit, or ceiling, of breeding snowy plovers to be:

Subpopulation	Ceiling size
OR	300
NC	200
SFB	500
MB	500
SLO	1600
SD	550

These ceilings are about 80 percent greater than current numbers, and are similar to, or slightly in excess of, estimates of target population size, obtained by snowy plover Recovery Team biologists, on a site by site basis (see Appendix B). A realistic assumption is that ceilings represent the maximum number of individuals that can successfully breed for each subpopulation. Under such an assumption, individuals in excess of the ceiling are still alive but cannot breed successfully in the current year. However, such an assumption cannot be implemented by RAMAS/GIS 2.0. Therefore, we made a more restrictive (and admittedly less realistic) assumption: individuals in excess of ceiling numbers do not survive the current year. This imposes a hard limit on maximum number of individuals in each subpopulation. Note that the metapopulation only reaches ceiling levels under Scenarios 17-19; in the other Scenarios, the metapopulation declines and/or is well below ceiling levels. Note also that there is no decrement in survival until the breeding population size **exceeds** the ceiling for that subpopulation.

Catastrophic Mortality - There is at present no evidence of catastrophic mortality in snowy plovers, but the 1998 El Niño may prove otherwise[1]. Though it may seem desirable to include catastrophic mortality, the problem is that we have no idea of its magnitude or frequency of occurrence. Thus any quantitative results (when this is included) depend entirely on the assumptions made. On the basis of input from Snowy Plover Recovery Team members we assume catastrophic mortality in the form of "reproductive failure." We assume that catastrophes occur, on average, once every 20 years (i.e., in each year with 5 percent probability), and that in a catastrophe year reproductive success is reduced to 50 percent of what it "normally" would have

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[1] It is believed that snowy plovers suffered unusually high winter mortality in the 1998 El Niño and the subsequent La Niña. Point Reyes Bird Observatory plans to examine this issue when appropriate data have been incorporated into the survivorship database (Gary Page, Point Reyes Bird Observatory, pers. comm. 2001).

been. Note that model results are identical whether reproductive success itself is impacted, as part of catastrophic mortality, or whether juvenile survival is impacted.   Catastrophes were assumed to occur independently of one another (i.e., the reproductive failure is specific to a subpopulation). We also consider a scenario with no catastrophic mortality and one in which catastrophic mortality includes reduction in adult survival (50 percent reduction compared to "normal" levels of survival, with a 5 percent probability per year) in addition to catastrophic reproductive failure.

All one-year-olds breed - This may be an overestimate but not likely by much; available field data (PRBO, unpubl.) indicate that the actual percent of males breeding is close to 100 percent. If we allow for less than 100 percent breeding among one-year-olds (or even among older adults), then results presented would be more pessimistic.

Weak, positive environmental correlations among subpopulations - This is a compromise between assuming strong correlations (for which there is no evidence) and assuming no correlation (which at least for survival would seem **unlikely**). Empirical data on reproductive success supports the assumption of weak, positive correlation among subpopulations.

Extinction Threshold
The Atlantic coast Piping Plover Recovery Plan had an objective of keeping the probability of extinction below 5 percent for the entire (meta)population in the next 100 years (U.S. Fish and Wildlife Service 1996). A scenario in which Pacific coast snowy plovers fall to a few individuals should not, in our opinion, be considered acceptable. Therefore, we consider the endpoint of "quasi-extinction," defined here as 50 individuals, rather than extinction itself (Burgman *et al*. 1993). This follows recommendations of Beissinger and Westphal (1998) and others. If there were as few as 50 individuals we expect that extreme measures would be undertaken to prevent extinction, such as captive breeding (as was the case for the California Condor). Also, an effective population size (N_e) of 50 individuals is considered close to the threshold number below which genetic and demographic forces combine, in the absence of intervention, to produce an "extinction vortex" (Gilpin and Soule 1986). It is difficult to determine what is the actual population size that corresponds to an effective population size of 50; for simplicity, in the results we present the probability that actual population size decreases below 50 individuals, but we recognize that N_e is always less than actual population size.

Results

Deterministic Results

With 76 percent adult survival, 50 percent juvenile survival, and fecundity = 1.105 (see above), the geometric rate of population growth (lambda) is 1.036, or 3.6 percent increase per year. All results in this section assume no stochastic effects (which are treated below) and in particular no catastrophic mortality. With 75 percent adult survival, and all other values the same, the growth rate decreases to 2.6 percent per year (lambda = 1.026). To produce a population growth rate of 1.0, requires 0.964 fledged young/male assuming 76 percent adult survival and 50 percent juvenile survival; if adult survival is 75 percent, 1.003 fledged young/male are required. Note that increasing fecundity by 0.037 chicks per male has an effect equivalent to increasing adult survival by 0.01 (i.e., decreasing adult mortality by 0.01, or 4 percent in relative terms).

Sensitivity analysis for Deterministic Results

A change in adult survival of 0.01 (0.75 to 0.76), produces a change in lambda of 1.0 percent. A change in fecundity of 8 percent (in relative terms), e.g. from 1.00 to 1.08, changes lambda by 2.24 percent. The same is true for a change in juvenile survival, e.g., increasing juvenile survival from 50 percent to 54 percent, changes lambda by 2.24 percent. Clearly, a small difference in adult survival (e.g., 1 percent) can have a substantial impact on population trajectory, especially over a 100-year time period.

Stochastic Results

We present results from 19 different scenarios for the Pacific coast Snowy Plover metapopulation. Each scenario differs with respect to one or more demographic parameters, or starting population size, or other assumptions (e.g., catastrophic mortality). In all cases, results from 400 replications of each scenario are shown. Scenario 1 is for **"Status Quo"** conditions: current values for reproductive success, etc., are assumed to continue indefinitely, i.e., management activities continue in OR, MB, and SD. Scenario 1 uses our best estimates for the suite of demographic parameters outlined above. This includes 76 percent adult survival and catastrophic reproductive failure, but no other catastrophic mortality. Results for Scenario 1 are summarized in Tables D-2A and D-2B. The overall trajectory for the metapopulation is shown in Fig. D-1A; shown also are the highest and lowest values obtained in the 400 simulations (depicted with diamonds), the mean outcome and also outcomes that are plus or minus one standard deviation. Thus, about 16 percent of outcomes will be above the mean + 1 S.D. level and about 16 percent of outcomes will be below the mean - 1 S.D. level. Furthermore, about 68 percent of outcomes, on average, will be within +/- 1 S.D. of the mean. We also depict two

examples of representative population trajectories, out of the total of 400 simulations (Fig. D-1B).

We see that even with continued levels of ongoing management into the future, the prognosis is for a slowly-decreasing metapopulation, one that, on average, declines at 0.92 percent per year (Table D-2A). After 100 years, the metapopulation can be expected to be 39 percent of its original size. The probability that the metapopulation will increase in 100 years is essentially zero (Fig. D-1A). On the other hand, the probability of quasi-extinction (fewer than 50 individuals) is also zero. Fig. D-1C depicts the probability of the metapopulation declining below specified levels. For example, there is a nearly 100 percent chance of declining below 1800 individuals (compared to the estimated 1950 at present), but only a 1 percent chance of declining below 200 individuals. The probability of at least a 50 percent decline after 100 years is 72 percent (Table D-2B). Results for individual subpopulations after 100 years are shown in Fig. D-1D; these show that, in almost all simulations, all six subpopulations are likely to persist for 100 years, but in some cases at very low levels (close to zero).

Sensitivity Analysis of Stochastic Results
In this section, we carry out a sensitivity analysis with respect to demographic parameters. We examine the effect of a change in one parameter (adult survival, juvenile survival, reproductive success, dispersal, or catastrophic mortality) on the future trajectory of the metapopulation, compared to Scenario 1. Such comparisons provide insight into the sensitivity of model outcomes to the assumptions made regarding each parameter, as well as providing insight into the response of the metapopulation to a change in a demographic parameter, either due to environmental alteration or to an anthropogenic effect.

Change in Adult Survival - In Scenario 2 adult survival is assumed to be 75 percent; all other parameter values and assumptions are as in Scenario 1. Compared to Scenario 1, the metapopulation declines at a faster rate - 1.59 percent per year, on average (Fig. D-2, Table D-2). After 100 years, the metapopulation will have declined on average by 80 percent (Table D-2A). The probability of quasi-extinction is 2.8 percent (Table D-2B), with an approximate 95 percent confidence interval about that estimate of 0 to 7.2 percent. There is nearly 100 percent probability that the metapopulation will decline by at least 32 percent after 100 years. The probability of at least a 50 percent decline after 100 years is 96 percent. These results confirm that a small change in adult survival can have potent effects on the long-term metapopulation trajectory. Scenario 3 demonstrates the sensitivity of results to a 1 percent increase in adult

survival. The metapopulation is still expected to decline, but at an even shallower rate compared to Scenario 1 - on average 0.46 percent per year, and 37 percent after 100 years (Table D-2A). The chance of any decline at all after 100 years is reduced to 96 percent. It would require a greater increase in adult survival (to above 78 percent) to produce a metapopulation whose long-term trajectory is essentially stable (Results not shown).

Change in Juvenile Survival - We consider two alternative scenarios. In Scenario 4, juvenile survival is reduced by 10 percent in relative terms, i.e., a reduction of .05 in absolute terms, from 0.50 to 0.45 probability of surviving. A difference in survival of 0.05 is not unreasonably large; it is less than the standard error of the most precise estimate available for juvenile survival (Table D-1). 0.05 is also the quantity by which we incremented the Monterey Bay juvenile survival estimate to account for permanent emigration. Results (Fig. D-3A, Table D-2) under this scenario depict a metapopulation that is quickly declining (at 2.8 percent per year, on average) and quickly approaches critical levels. Under Scenario 4, there is a 42 percent chance of quasi-extinction. The probability of a 50 percent decline is essentially 100 percent. In fact, in 50 percent of the simulations, the metapopulation declines by 96 percent or more.

Scenario 4 shows the stark effects of a 10 percent relative change in juvenile survival. But what about the impact of more subtle changes in juvenile survival? To answer that question, in Scenario 5, we consider a 4 percent decrease, in relative terms, of juvenile survival, from 0.50 to 0.48. Note that from the point of view of a change in **mortality** (rather than survival), a change in juvenile survival from 0.50 to 0.48 implies a 4 percent relative increase in mortality, just as does a change in adult survival from 0.76 to 0.75. Results (Table D-2, Fig. D-3B) in this scenario demonstrate a metapopulation that declines with 100 percent probability, with an average decline of 1.5 percent per year, and a 78 percent decline after 100 years. Moreover, in 100 percent of simulations metapopulation size decreased by at least 26 percent. However, the probability of quasi-extinction is low, 3.5 percent (Table D-2B). We conclude that relatively small changes in juvenile survival will have sizeable impacts on long-term population trends, but will not have large effects on quasi-extinction probabilities.

Change in Reproductive Success - In the age-structured model used in the population viability analysis, a change in juvenile survival of k percent is exactly equivalent to a change in reproductive success (fledglings per male adult) of k percent. This is because only the product of juvenile survival x reproductive success is modeled. Hence, Scenarios 4 and 5 (discussed above) demonstrate the effects of a 10 percent and 4 percent change, respectively, *in reproductive*

success, just as they do for a change in juvenile survival. We also consider sensitivity of model results to assumptions about reproductive success of just the SLO subpopulation. In Scenarios 1-5 above, an intermediate value of reproductive success was assumed for the SLO subpopulation (0.919 fledged young per male). Scenario 6, instead, assumes an optimistic value of 0.988 fledged chicks per male; i.e., that value of reproductive success which would produce a stable, self-sustaining population in the absence of immigration and emigration. Scenario 7, instead, assumes a pessimistic value of 0.849 fledged chicks per male; i.e., the same reproductive success as assumed for NC and SFB and as observed in Monterey Bay in the absence of intensive management. Results are summarized in Tables D-2A and D-2B. The effect of a 7.5 percent relative change in SLO reproductive success, either an increase (Scenario 6) or a decrease (Scenario 7), is fairly minor. For example, comparing Scenarios 1 and 6, lambda for the metapopulation increases slightly from 0.9908 to 0.9926, a difference of less than 0.2 percent (Table D-2A). The chance of a 50 percent decline for the metapopulation decreases from 72 percent (Scenario 1) to 59 percent (Scenario 6) (Table D-2B). Similarly, comparisons of Scenarios 7 and 1, indicate only minor differences (Table D-2). We conclude that, though reproductive success for SLO cannot be estimated with great certainty, results of the population viability analysis are not very sensitive to assumptions made regarding this parameter, providing they are within a reasonable range (bounded by the optimistic and pessimistic values considered).

Change in Catastrophe - Scenario 8 assumes no catastrophic reproductive failure at all. Compared to Scenario 1, the effect of eliminating catastrophic reproductive failure is to increase lambda slightly, by 0.3 percent (0.9938 instead of 0.9908; Table D-2A). However, the absence of catastrophic failure results in a substantial reduction in risk of metapopulation decline, from 72 percent chance of a 50 percent decline to a 42 percent probability in Scenario 8 (Table D-2B). An even larger impact on the risk of metapopulation decline is observed in Scenario 9, in which catastrophic mortality of adults is added to catastrophic reproductive failure in years of catastrophe. In Scenario 9, lambda decreases substantially, to 0.9763 (Table D-2A). Under this scenario, we expect, on average, a 91 percent decline in metapopulation size. In addition, the risk of quasi-extinction is 29 percent, with a 99 percent probability that the metapopulation decreases by at least 50 percent after 100 years (Table D-2B). These results demonstrate that a relatively rare catastrophic event (5 percent probability per year) can have a large long-term effect on population growth and risk, if it entails a substantial increase in adult (and possibly juvenile) mortality. If catastrophes are as common as is assumed in Scenario 9, then the risk of metapopulation decline will be severely underestimated by any model which does not incorporate catastrophes.

Change in Dispersal - Here we consider the impact of a 50 percent and a 100 percent decrease in dispersal rates (Scenarios 10 and 11, respectively). That is, in Scenario 10 all dispersal rates were reduced by 1/2, and in Scenario 11, we assumed no dispersal whatsoever among subpopulations. The dynamics of the metapopulation as a whole were not much affected by even large changes in dispersal rates (Tables D-2A and D-2B). With a 50 percent reduction in dispersal (Scenario 10), the population growth rate increased slightly to lambda = 0.9914, that is, the metapopulation declined at an average of 0.86 percent per year instead of 0.92 percent (Scenario 1). The probability of quasi-extinction remained essentially zero, and the probability of a 50 percent decline after 100 years was little changed (71 percent instead of 72 percent for Scenario 1). Even when dispersal was eliminated the dynamics were not altered greatly. In the latter case, lambda decreased to 0.9906, almost identical to that observed in Scenario 1. The probability of a 50 percent decline after 100 years increased somewhat, from 72 percent in Scenario 1 to 79 percent in Scenario 11.

A 50 percent reduction in dispersal rates, also had only minor effects on the expected sizes of the six subpopulations after 100 years (Fig. D-4A; cf. Fig. D-1D). The most notable difference is an increased size of the MB subpopulation with reduced dispersal. With the elimination of dispersal, two subpopulations could be expected to go completely extinct with more than 50 percent probability, NC and SFB (Fig. D-4B). We conclude that within the likely range of dispersal rates, model results are not very sensitive to the exact parameter values used.

Changes in Management
We consider the impact of changes in management practice that may increase or decrease reproductive success. It is possible for changes in management practice to impact other demographic parameters, but we consider that possibility less likely.

Scenario 12 assumes "**No Management**". We assume cessation of management in OR, MB, and SD and that the other subpopulations continue as in the present (i.e., as in Status Quo, Scenario 1). In Scenario 12, reproductive success is assumed to be 0.849 chicks per male for OR, MB, and SD, just as it is for NC and SFB. All other parameter values are as in Scenario 1. The expected outcome under this Scenario is for the metapopulation to show a strongly declining trend (Fig. D-5A, Table D-2A). Likelihood of decrease below specified population levels (for the entire metapopulation) is shown in Fig. D-5B. The probability that the metapopulation will decline by at least 50 percent after 100 years is 100 percent. In fact, there is a 100 percent probability of at least a 77 percent decline (Fig. D-5B). The probability of quasi-extinction is 51

percent (Table D-2B). Clearly, the abandonment of management that protects snowy plovers is an unpalatable alternative.

Scenario 13 is a modification of Scenario 12. In Scenario 13, metapopulation size is assumed to begin with 3500 individuals, close to, and slightly in excess of, the number of individuals for which there is at present available beach habitat. One can imagine that intensive management resulted in an increase in snowy plover numbers until a population size of 3500 was reached, but that once reached, management activities ceased. In other words, Scenario 13 differs from Scenario 12 only with respect to starting population sizes. It is also assumed that with a metapopulation size of 3500, all ceiling values are increased by 10 percent (i.e., to 3850 breeding individuals). As expected, the metapopulation shows the same steep population decline as in Scenario 12 (Table D-2A). In one sense, all Scenario 13 does (compared to Scenario 12) is to buy some time for the metapopulation. After 21 years, the metapopulation has decreased from 3500 individuals to about 1950, the starting level for Scenario 5. After 100 years, the probability that the metapopulation has fallen below 50 individuals is 35 percent (cf. to 51 percent for Scenario 5). There is a 100 percent probability that the population will decline at least 85 percent. These results demonstrate that simply increasing population size is not a viable solution for the snowy plover metapopulation.

We next considered scenarios in which reproductive success is enhanced. In the next four scenarios we assumed that management continues in OR, MB, and SD, as it has, and that, therefore, fecundity and other parameter values continue as at present. In the first of these (Scenario 14), we assume that management activities in SLO (the largest subpopulation) results in an increase in fecundity to that obtained in MB now (i.e., 1.105 chicks fledged per breeding male). Results are shown in Fig. D-6, indicating that, on average, the population declines, albeit at a very slight rate (0.3 percent decline per year; Table D-2A). There is an 85 percent chance of at least some decline, and a 19 percent chance of a 50 percent decline (Table D-2B). The probability of quasi-extinction is zero.

In the next scenario (Scenario 15), it is assumed that management activities at SLO are not quite as effective, and that reproductive success can only be increased to 1.0 fledged chicks per male. In this case, population growth rate declines at, on average, 0.7 percent per year (Table D-2A). As a result, there is a 51 percent probability of at least a 50 percent decline, over 100 years. While, this result is an improvement over the results of the Status Quo scenario (Scenario 1), it would still not be considered a desirable outcome.

An alternative scenario (Scenario 16) is for management action to increase reproductive success in NC and SFB, with SLO remaining as it is now. Results of Scenario 16 are a slight decline, just as in Scenario 14 (0.3 percent decline per year; Table D-2A). However, results from this scenario indicate less variability of outcome (Fig. D-7) compared to Scenario 14, in which SLO reproductive success was enhanced. As a result, the probability of a 50 percent decline is only 6 percent (Table D-2B). The probability of quasi-extinction is zero.

Comparison of results from Scenarios 14 and 16 indicate that increases in reproductive success of either SLO or SFB and NC would be effective in stabilizing snowy plover numbers, and reducing the risk of substantial population decline in the future.

None of the scenarios presented above result in likely population increase. We therefore considered three additional metapopulation scenarios (Scenarios 17-19). In Scenario 17, management at SLO, NC, and SFB are such that all three subpopulations achieve fecundity of 1.105 chicks reared per breeding male (with the other three subpopulations as assumed above). Under this scenario the metapopulation does show an increase, but a surprisingly shallow increase: lambda = 1.0013 (Table D-2A), an annual growth rate of 0.13 percent per year. At the end of 100 years, the metapopulation is expected to grow by a total of 14.4 percent, on average. The relatively flat trajectory is surprising because we expected numbers to show an increase to close to ceiling levels, an 87 percent increase if all ceiling levels were attained. It turns out that some subpopulations achieved ceiling levels while others did not (Fig. D-8). Fig. D-8 demonstrates that (under assumptions of the model), OR, NC, SFB, and MB, were on average close to their ceiling levels, but SLO and SD are not. SLO and SD numbers would increase much further if excess individuals at other subpopulations (above ceiling levels) were to disperse to SLO and SD; however, such selective dispersal was not incorporated into the simulations, nor is it possible to do so using the RAMAS/GIS 2.0 program. Therefore, we consider the results from Scenario 17 to be somewhat unrealistic, since they incorporate unrealistic assumptions about dispersal when subpopulation size is at or near ceiling levels. A more sophisticated modeling program is required to incorporate assumptions about the dependence of dispersal on population size relative to population ceiling size.

Finally, we considered two scenarios in which population increase can be expected to reach 3000 snowy plovers within a 25 year period. In the first of these (Scenario 18), reproductive success is assumed to be 1.3 chicks per male for all subpopulations. This level of reproductive success is high, but attainable; in 1998, snowy plovers in the Monterey Bay study area achieved this level of

reproductive success. This scenario assumes that with sufficiently intensive management, all subpopulations will be able to achieve this level of reproductive success at some time in the future. Under this scenario, there is an 82 percent chance of the population reaching 3000 or more birds at the end of 25 years (see Table D-3). At first the size of the metapopulation increases rapidly, but the rate of growth slows down beyond year 10 (Fig. D-9), and then shows very slow growth beyond year 15.

The last scenario (Scenario 19) assumes that reproductive success of 1.2 chicks fledged per male is achieved for all subpopulations. Under this scenario, there is a 57 percent chance that the metapopulation will contain 3000 or more individuals after 25 years. The median outcome after 25 years is 3110 individuals, which is only 540 less than the overall maximum allowed for the metapopulation. Scenarios 18 and 19 demonstrate that there is a reasonably high probability of achieving at least 3000 birds within 25 years, provided that reproductive success averages 1.2 or more chicks per male over all subpopulations.

Discussion

In all modeling exercises, the results are sensitive to the assumptions. In this case we have tried to make assumptions explicit and we have examined the influence of the assumptions (or assumed values) on model results. The strength of the current analysis is that demographic estimates were based on data gathered from study populations within the Pacific coast metapopulation. An important feature of the population viability analysis is the use of a metapopulation structure that allows estimates for parameters to vary among subpopulations. We consider it highly desirable for population viability analyses to incorporate such flexibility.

Reproductive Parameters
That we could allow for subpopulation-specific parameters is a boon, yet the lack of available estimates for several of the subpopulations constitutes a drawback to the population viability analysis. In particular, no demographic parameter estimates are available for the SLO subpopulation, which is estimated to contain 45 percent of the entire metapopulation. Obtaining fecundity estimates for this subpopulation, as well as for NC and SFB, should be a priority. Even when we assumed that reproductive success in SLO was sufficiently high to produce a self-sustaining population, the metapopulation, on average, showed a decline at 0.74 percent per year, under the Status Quo conditions ("optimistic" scenario, Scenario 6). On the other hand, if reproductive success in SLO is as low as 0.849 chicks per breeding male ("pessimistic" Scenario,

Scenario 7) then the metapopulation would be expected to decline at a faster rate, at 1.1 percent per year. Though it would be desirable to obtain estimates from the SLO subpopulation itself, the sensitivity analyses demonstrated that results were not unduly sensitive to the estimate of reproductive success for this subpopulation, if SLO reproductive success was within the range of values modeled.

Dispersal

Theoretical studies have demonstrated that dispersal among subpopulations will reduce the chance of extinction of the metapopulation (Burgman et al. 1993, Harrison 1994), compared to a set of isolated subpopulations. In this case, we had reasonably good empirical data from the Monterey Bay study population, indicating dispersal rates of 20 percent to 25 percent among first-year birds. An area of uncertainty was whether dispersal rates varied with density (Beissinger and Westphal 1998). Recent observations of snowy plovers indicate that dispersal occurs at high and low densities, and therefore we did not include density-dependent dispersal in the modeling. However, there may be a threshold effect: once a breeding area (e.g., beach) is saturated, dispersal from that area may be enhanced. Future modeling could address this possibility, and its implications. Though our knowledge of dispersal was incomplete, it did not appear that model results were very sensitive to assumed dispersal rates. In particular, a 50 percent relative reduction in dispersal had almost no discernible effect on the metapopulation trajectory, persistence, or on subpopulation composition. This provides us with some confidence in model results despite the acknowledged uncertainty in dispersal rates.

Adult and Juvenile Survival

The sensitivity analysis (Scenarios 2-11) demonstrated a strong effect of inclusion of catastrophic mortality of adults. It is possible that the El Niño of 1998 will demonstrate such catastrophic mortality, but such a phenomenon cannot be demonstrated until completion of the 1999 breeding season, at the earliest. The sensitivity analysis also confirmed the sensitivity of metapopulation trajectory to moderately large changes in reproductive success and/or juvenile survival. We did not examine the sensitivity of results to a moderately large long-term change in adult survival, but even a small change (1 percent change in absolute survival) had a noticeable effect on metapopulation trajectory. Nevertheless, the probability of quasi-extinction was low whether adult survival was 75 percent (Scenario 2), 76 percent (Scenario 1), or 77 percent (Scenario 3). We conclude that, in general, the results shown are applicable, assuming that adult survival was between 75 percent and 77 percent. We consider it unlikely that adult survival was much lower than 75 percent. At the same time, there is no support for assuming that adult survival was

greater than 77 percent. Adult survival would have to be greater than 78 percent (Results not shown) to produce a metapopulation that is likely to grow, and even then it would only be growing slowly.

In most Scenarios, we assumed 50 percent juvenile survival. Though juvenile survival was surely at least 45 percent, it is debatable just how much greater it is than 45 percent. Thus, our results could be considered a bit liberal, or optimistic. If juvenile survival was actually lower than 50 percent (as in Scenarios 4 and 5) population trends would be more pessimistic.

Limitations to the Population Viability Analysis

There are several limitations to the population viability analysis. First, we did not include risk to the metapopulation due to genetic factors. Such a simplification (ignoring genetic factors) is consistent with recommendations of Beissinger and Westphal (1998). Genetics would become much more important to consider if metapopulation size would likely decrease to low levels, that is, 50 or fewer. However, population viability analysis results here indicate decrease to such low levels unlikely.

Second, we did not take into account an "Allee effect," which is a decrease in survival or reproductive success with a decrease in population size, usually due to social factors. For example, Allee effects can arise if individuals have difficulty securing mates when density is low. However, we believe that as long as metapopulation size remains at 50 or more (see above), Allee effects are not likely important.

The use of a packaged program (RAMAS/GIS) had the advantages of convenience, reproducibility, and general availability. Balancing that were limitations of that particular program. As already mentioned, dispersal was modeled at a constant rate and does not vary stochastically. Dispersal cannot vary with the size of the target population. Nor can one specify a constant number of dispersers. Thus, for example, one cannot specify balanced dispersal (dispersal from the population exactly equals dispersal to that population). Furthermore, with RAMAS/GIS dispersal cannot be modeled as a threshold phenomenon (e.g., dispersal only for those in excess of carrying capacity). Even if dispersal could be modeled in very sophisticated ways, we are limited by the lack of information regarding dispersal. Other limitations of RAMAS/GIS included the requirement that temporal covariation of population parameters is 100 percent. If it is a very good year for survival, the program assumes it is a very good year for reproductive success. There are many limitations on modeling density dependence with RAMAS/GIS. For example, we could not model a "ceiling effect" on reproductive success (i.e.,

individuals in excess of the ceiling do not reproduce), and had to assume that excess individuals were dead.

Tentative Conclusions

Results from this population viability analysis highlight the need for increased management of Pacific coast western snowy plovers and their habitats. Under status quo scenarios, even with intensive management in some areas, the population is almost certain to decline. Without question, ceasing current management efforts (area closures, predator exclosures, and predator control) would be disastrous for the Pacific coast population. The Snowy Plover Recovery Team, however, has identified population growth as a prerequisite to recovery. The most direct means to increase population size will be to enhance reproductive success throughout the western snowy plover range. The model suggests that productivity of **at least** 1.0 chicks fledged per breeding male per year should result in a stable population, if our estimates of adult and juvenile survivorship are accurate. Productivity of 1.2 or more chicks fledged per breeding male should increase population size at a moderate pace before growth slows as the metapopulation approaches its ceiling. Population growth would be hastened, of course, if survival of adults or juveniles can also be improved. Under this population growth scenario, the metapopulation could increase to 3000 individuals within the relatively short time span of 25 years. Recovery is plausible. It will require, however, short-term intensive management and long-term commitments to maintaining gains.

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Table D-1. Snowy plover demographic parameter estimates.

A) Percent adult male survival, for males, excluding first-year after banding.

	All Observations (including Winter)	Expanded Area (Breeding Season only)	Single Study Area (Breeding Season only)
Monterey Bay	74.7 $\pm$ 1.9	74.3 $\pm$ 1.9	73.7 $\pm$ 3.6
Oregon	74.5 $\pm$ 13	74.3 $\pm$ 8.5	73.6 $\pm$ 18
San Diego	71.3 $\pm$ 9.0	71.3 $\pm$ 9.0	71.3 $\pm$ 16

Notes: Observed between-year standard deviation in Monterey Bay = 5.65 percent; mean adult male survival used in the population viability analysis is 76 percent (also 75 percent and 77 percent, see text).

B) Percent Juvenile (1st Year) survival, post-fledging.

	All Observations (including Winter)	Expanded Area (Breeding Season only)	Single Study Area (Breeding Season only)
Monterey Bay	45 $\pm$ 15	44 $\pm$ 6.7	39 $\pm$ 12
Oregon	51 $\pm$ 40	49 $\pm$ 53	44 $\pm$ 65
San Diego	45 $\pm$ 22	43 $\pm$ 15	42 $\pm$ 16

Notes: Between-year standard deviation = 6.8 percent for Monterey Bay. Juvenile survival used in population viability analysis = 50 percent (also 48 percent and 45 percent, see text).

C) Fecundity (chicks reared to fledging, per adult male).

Study Population	Years	Mean	Between-year standard deviation
Monterey Bay w/o predator control	1984-1991	0.849	0.173
Monterey Bay w/ predator control	1992-1997	1.105	0.157
Oregon	1993-1997	1.040	---
San Diego	1995-1997	0.917	---

Table D-2. Summary of stochastic results, after 100 years (400 simulations each scenario).

A. Summary of long-term population trajectories.

Scenario No.	Description	Minimum	X - S.D.	Mean	X + S.D.	Lambda	Percent Change
1	Status Quo (SQ)	61	410	771	1131	0.9908	-61
2	SQ but 75 percent adult survival	0	127	391	654	0.9841	-80
3	SQ but 77 percent adult survival	182	817	1232	1647	0.9954	-37
4	Juvenile survival or reproductive success reduced 10 percent	0	5	118	231	0.9723	-94
5	Juvenile survival or reproductive success reduced 4 percent	3	134	437	740	0.9851	-78
6	SQ but optimistic SLO reproductive success estimate	28	511	930	1348	0.9926	-52
7	SQ but pessimistic SLO reproductive success estimate	28	306	639	972	0.9889	-67
8	SQ, no catastrophic mortality	147	669	1044	1419	0.9938	-46
9	Catastrophic mortality includes survival and reproductive failure	0	0	177	362	0.9763	-91
10	Dispersal reduced by 1/2	85	453	825	1196	0.9914	-58
11	No dispersal	7	448	757	1066	0.9906	-62
12	No management	0	5	86	166	0.9692	-96
13	Start with 3500 total; no management	0	16	116	215	0.9722	-94
14	Improve SLO reproductive success to 1.105 chicks	198	934	1445	1957	0.9970	-26
15	Improve SLO reproductive success to 1.0 chicks	80	560	975	1389	0.9931	-50
16	Improve NC and SFB reproductive success to 1.105 chicks	601	1138	1440	1742	0.9970	-26
17	Improve reproductive success at SLO, NC and SFB to 1.105 chicks	1018	1741	2230	2718	1.0013	14.4

Note: The last column shows mean total percent decline after 100 years, except for Scenario 17, for which percent increase is shown.

Table D-2. Summary of Stochastic Results, continued

B. Probability of Quasi-extinction and Probability of Specified Declines during 100 years.

Sce-nario No.	Description	Probability of Quasi-Extinction, percent[1]	Probability of any decline, as percent	Probability of 50 percent decline, as percent	Median percent decline[2]
1	Status Quo (SQ)	0	100	72	61
2	SQ w/ 75 percent Adult Survival	2.8	100	96	83
3	SQ w/ 77 percent Adult Survival	0	96	27	36
4	Juvenile Survival/reproductive success reduced 10 percent	42	100	100	96
5	Juvenile Survival or reproductive success reduced 4 percent	3.5	100	92	81
6	SQ + optimistic SLO reproductive success estimate	0.3	100	59	54
7	SQ + pessimistic SLO reproductive success estimate	0.3	100	83	69
8	SQ, no catastrophic reproductive failure	0	100	42	46
9	Catastrophic mortality includes survival and reproductive failure	29	100	99	94
10	Dispersal reduced by 1/2	0	100	71	59
11	No dispersal	0.3	100	79	64
12	No management	51	100	100	97
13	Start with 3500; no management	35	100	100	97
14	Improve SLO reproductive success to 1.105 chicks	0	85	19	26
15	Improve SLO reproductive success to 1.0 chicks	0.3	99	51	50
16	Improve NC and SFB reproductive success to 1.105 chicks	0	97	6	25
17	Improve reproductive success at SLO, NC and SFB to 1.105 chicks	0	30	0	12[2]

[1] - Standard error of the estimate of Probability of Quasi-extinction is $\pm$ 2.2 percent in all cases.

[2] - Median percent increase in total population size.

Table D-3. Summary of results for growth scenarios, at the end of 25 years.

Sce-nario No.	Description	Median outcome after 25 years, N	Probabi-lity of 3000+ after 25 years, percent	Population size reached after 25 years with 80 percent probability, N	Percent annual growth rate in first 15 years[1]
18	Improve reproductive success to 1.3 chicks per male in all subpopulations	3341	82	3018	3.35
19	Improve reproductive success to 1.2 chicks per male in all subpopulations	3110	57	2740	2.95

[1] - Annualized growth rate, calculated for first 15 years.

A   Trajectory summary
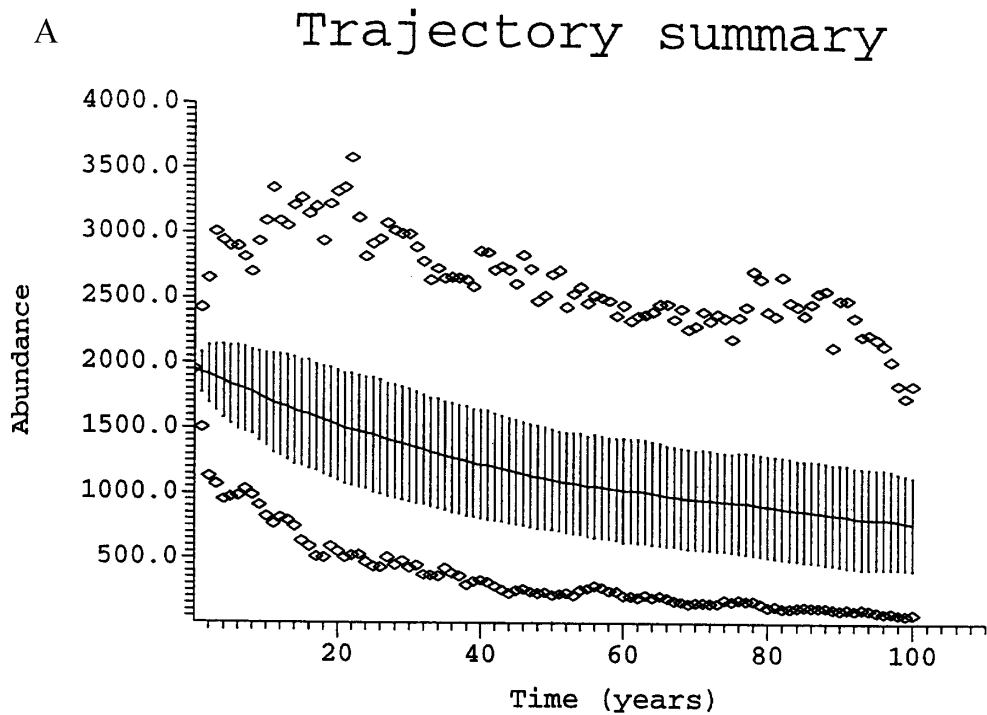
Figure D-1. Scenario 1: Status Quo (see text). A) Population trajectory for the metapopulation. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome. B) Population trajectories for two sample simulations (among 400), under Scenario 1. C) Probability that after 100 years the metapopulation will have declined below specified level. Dotted lines indicate approximate 95 percent confidence interval. D) Abundance for each subpopulation (abbreviated as in text) at the end of 100 years. Bars indicate means, vertical lines with bars indicate + 1 standard deviation. Diamonds show maximum (among 400 simulations).

B Trajectory summary
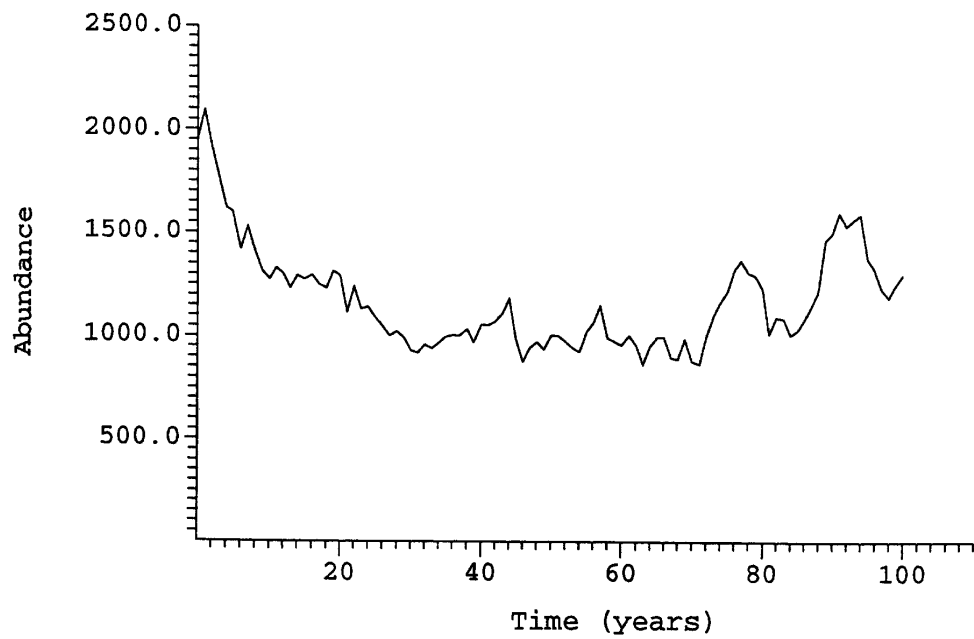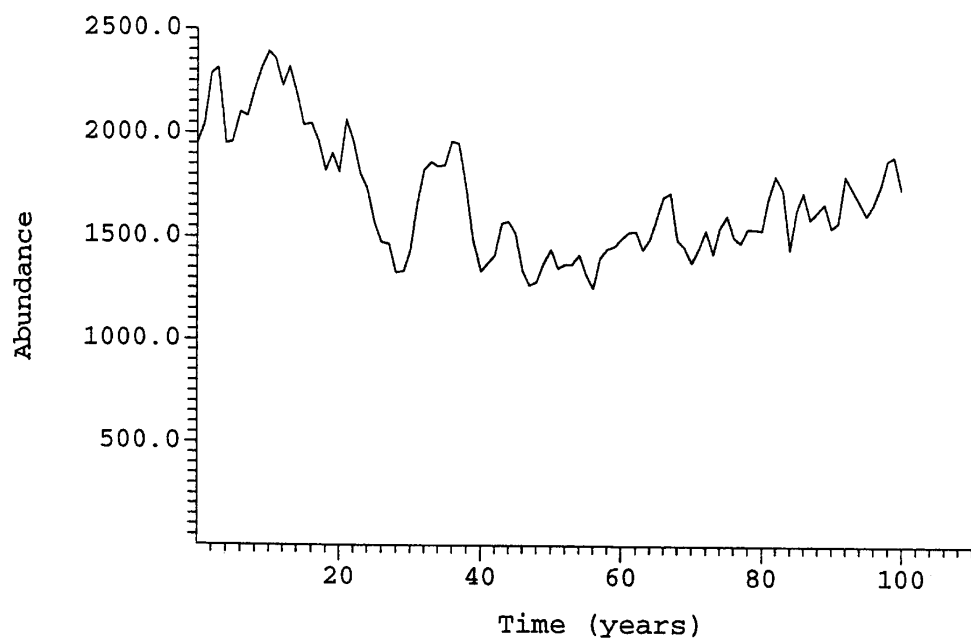
C
Terminal percent decline
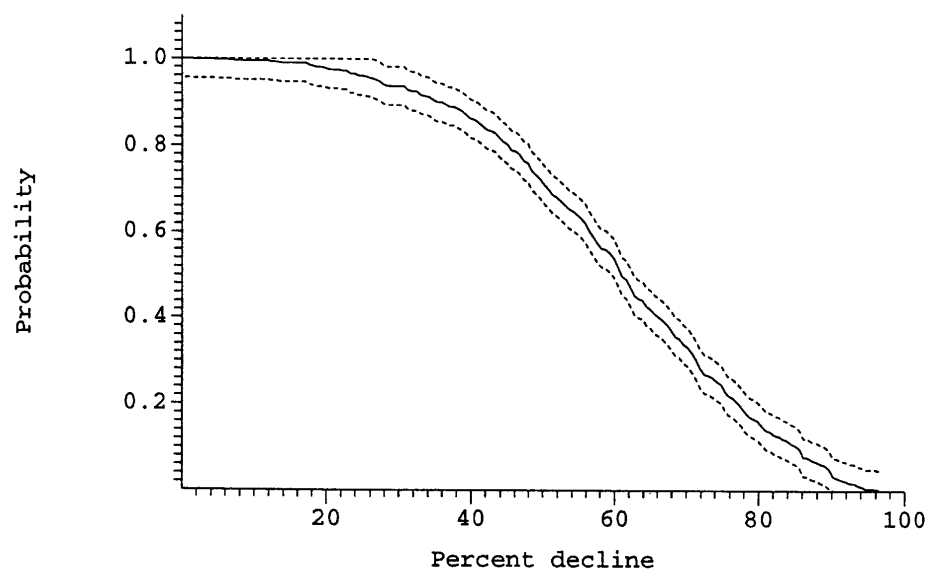
D
Population structure
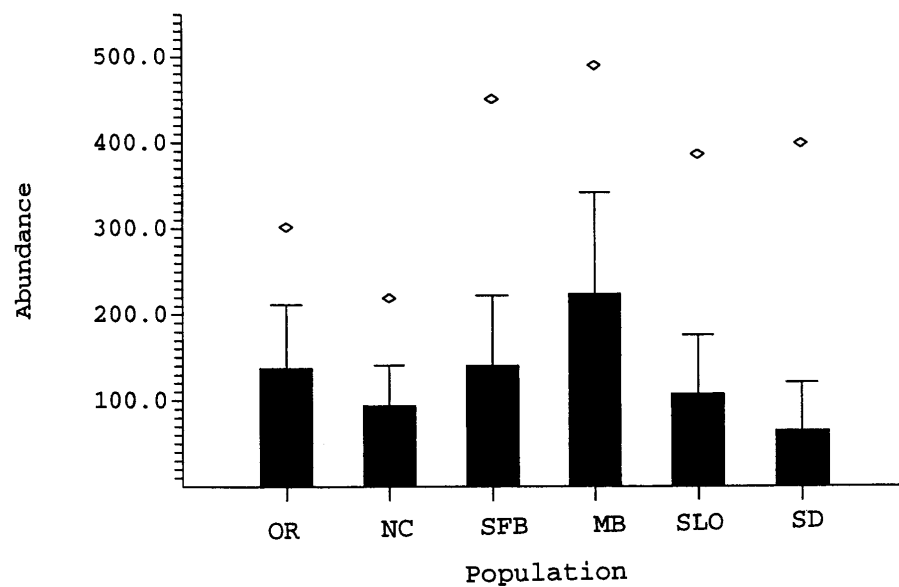
Trajectory summary
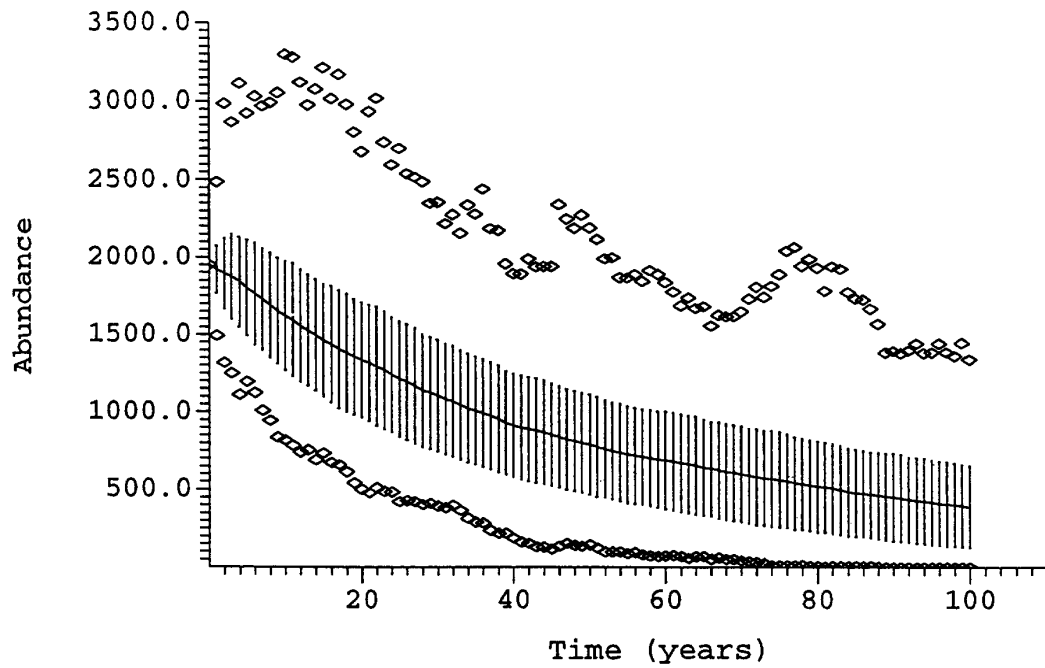
Figure D-2. Scenario 2: Status Quo with 75 percent adult survival instead of 76 percent. Population trajectory for the metapopulation. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome.
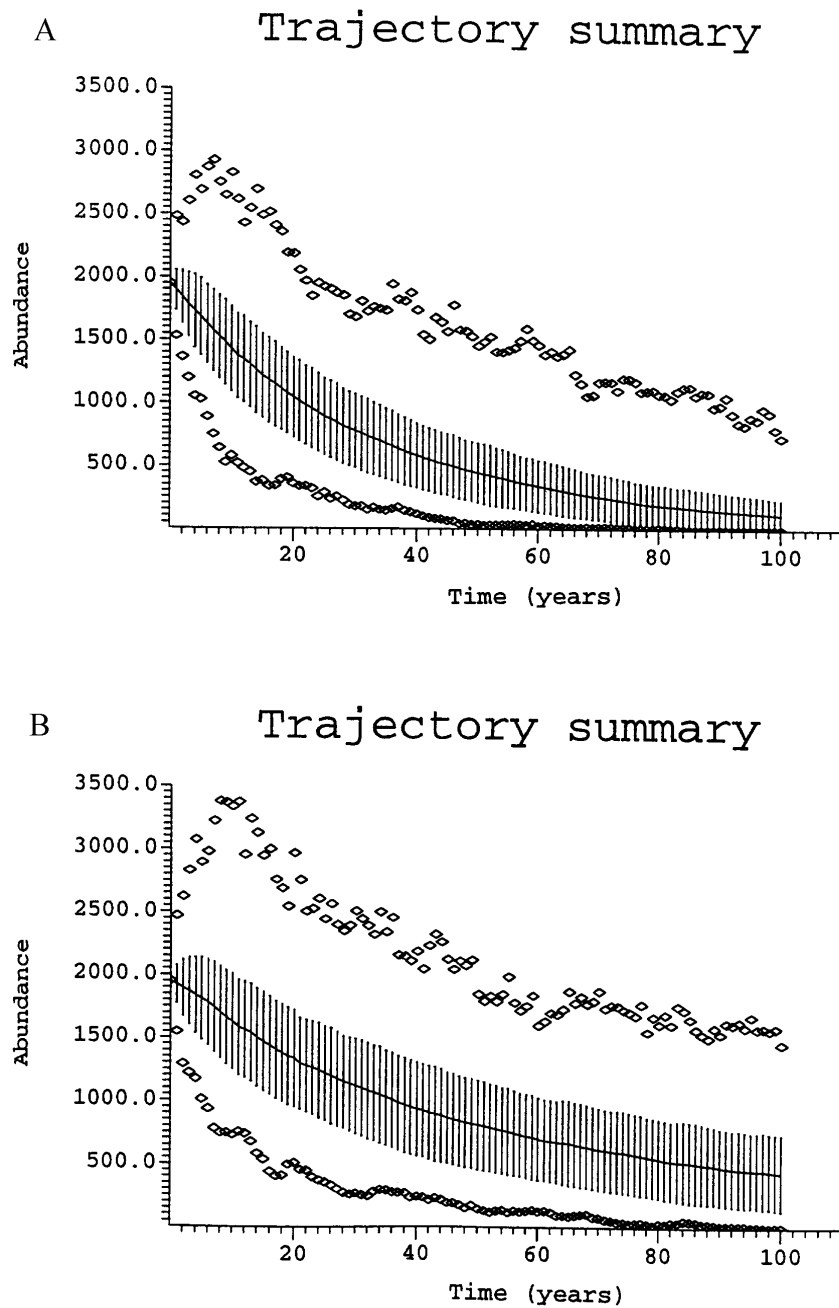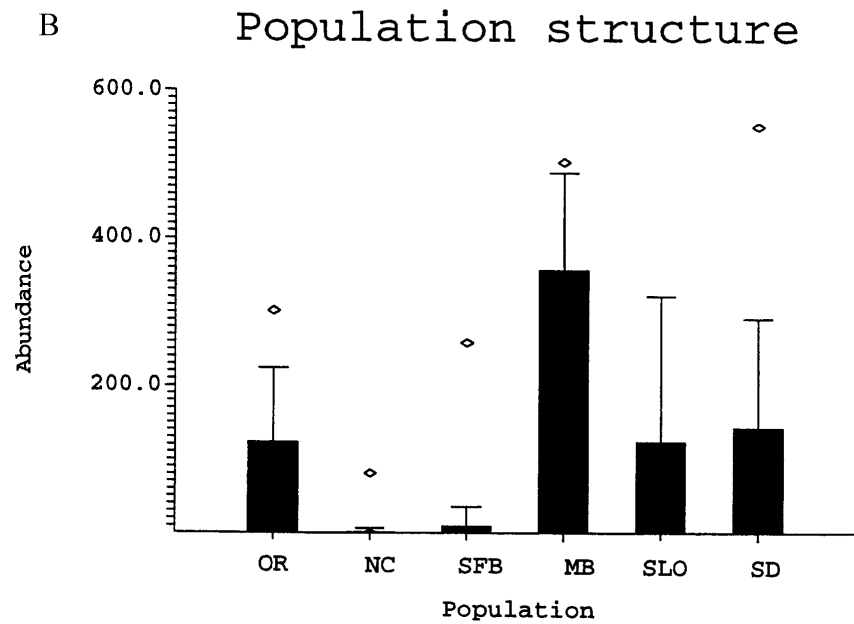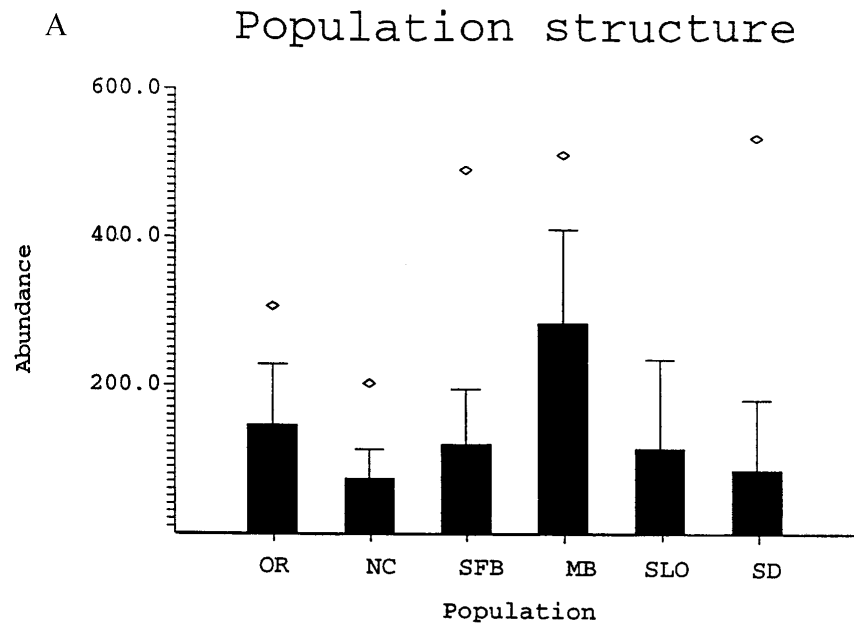
Figure D-3. Scenarios 4 and 5: Status Quo with reduction in juvenile survival (equivalently, reproductive success) by 10 percent (A) and by 4 percent (B). In each Figure panel: Population trajectory for the metapopulation. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome.

A Population structure

B Population structure

Figure D-4. Scenarios 8 and 9: Status Quo with reduction in dispersal. A) Dispersal reduced by 1/2 (Scenario 8). B) No dispersal (Scenario 9). For each Figure panel: Abundance for each subpopulation at the end of 100 years. Bars indicate means; vertical lines with bar indicate +1 standard deviation. Diamonds show maximum (among 400 simulations).
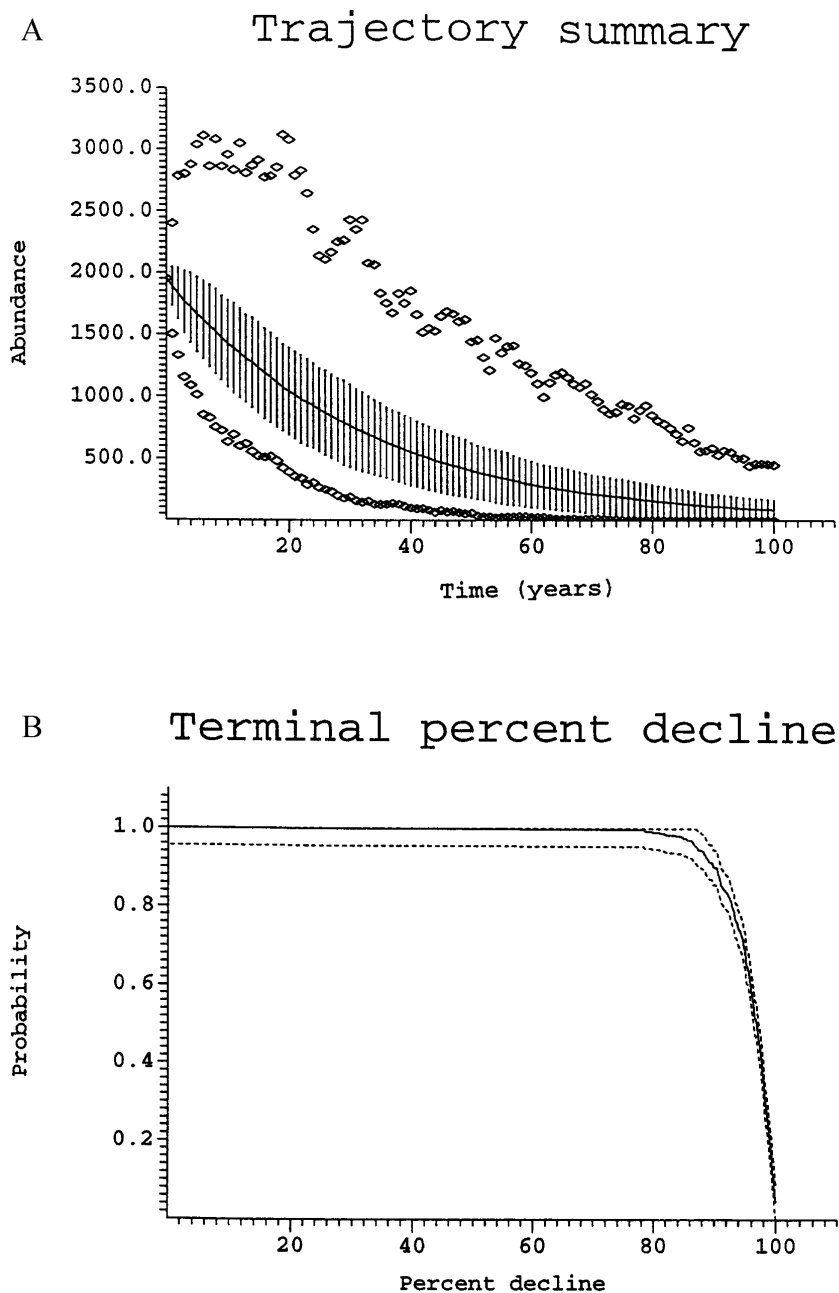
A   **Trajectory summary**

B   **Terminal percent decline**

Figure D-5. Scenario 12: No Management. A) Population trajectory for the metapopulation. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome. B) Probability that at the end of 100 years the metapopulation will have declined below specified level. Dotted lines indicate approximate 95 percent confidence interval.

D-36

Trajectory summary
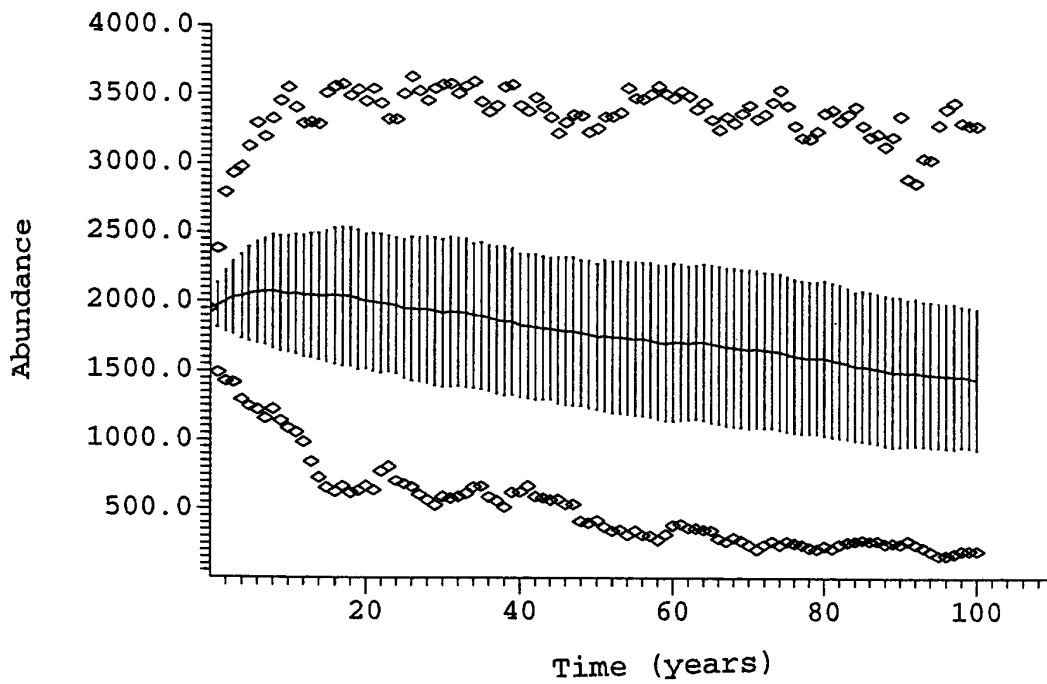
Figure D-6. Scenario 14: Improve reproductive success in San Luis Obispo/Santa Barbara/Ventura subpopulation and Status Quo elsewhere; see text. Population trajectory for the metapopulation. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome.
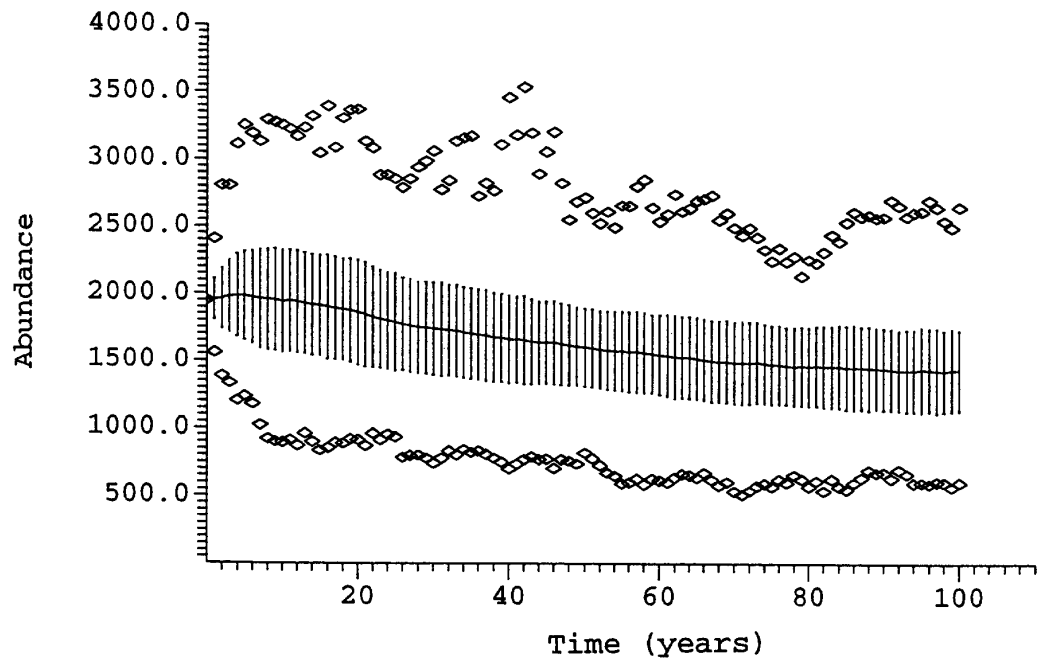
Figure D-7. Scenario 16: Improve reproductive success in San Francisco Bay and Northern California Coast subpopulations, Status Quo elsewhere; see text. Population trajectory for the metapopulation. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome.
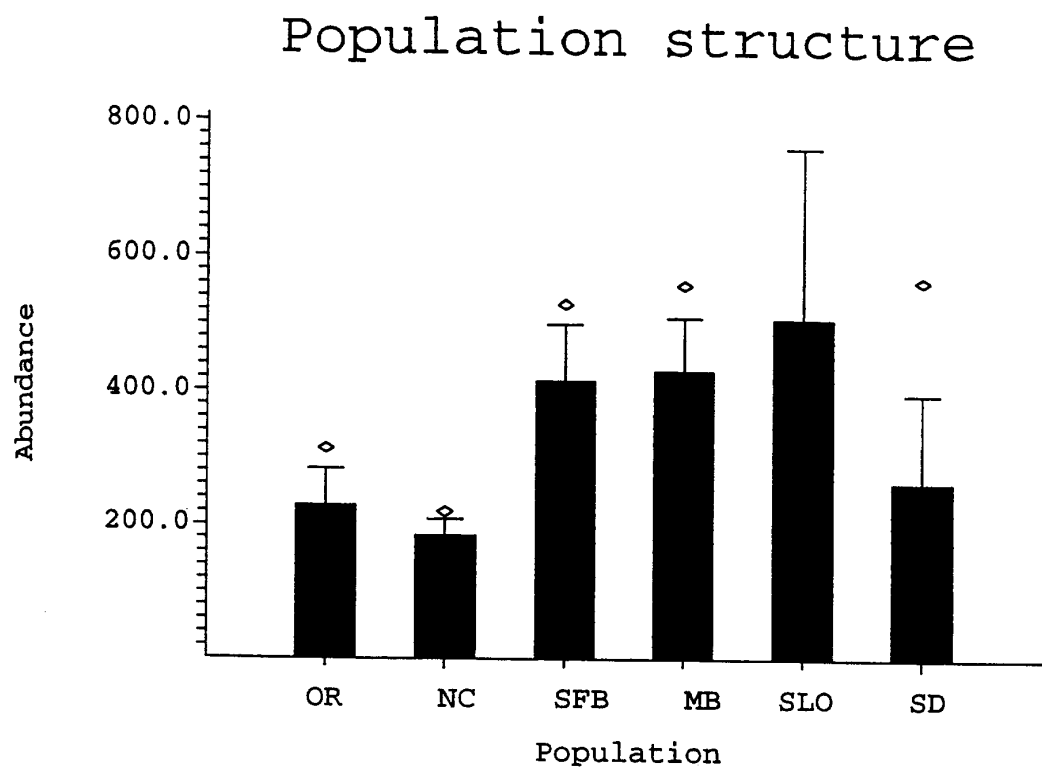
Population structure

Figure D-8. Scenario 17: Management at all areas (see text). Abundance for each subpopulation at the end of 100 years. Bars indicate means; vertical lines with bars indicate + 1 standard deviation. Diamonds show maximum (among 400 simulations).
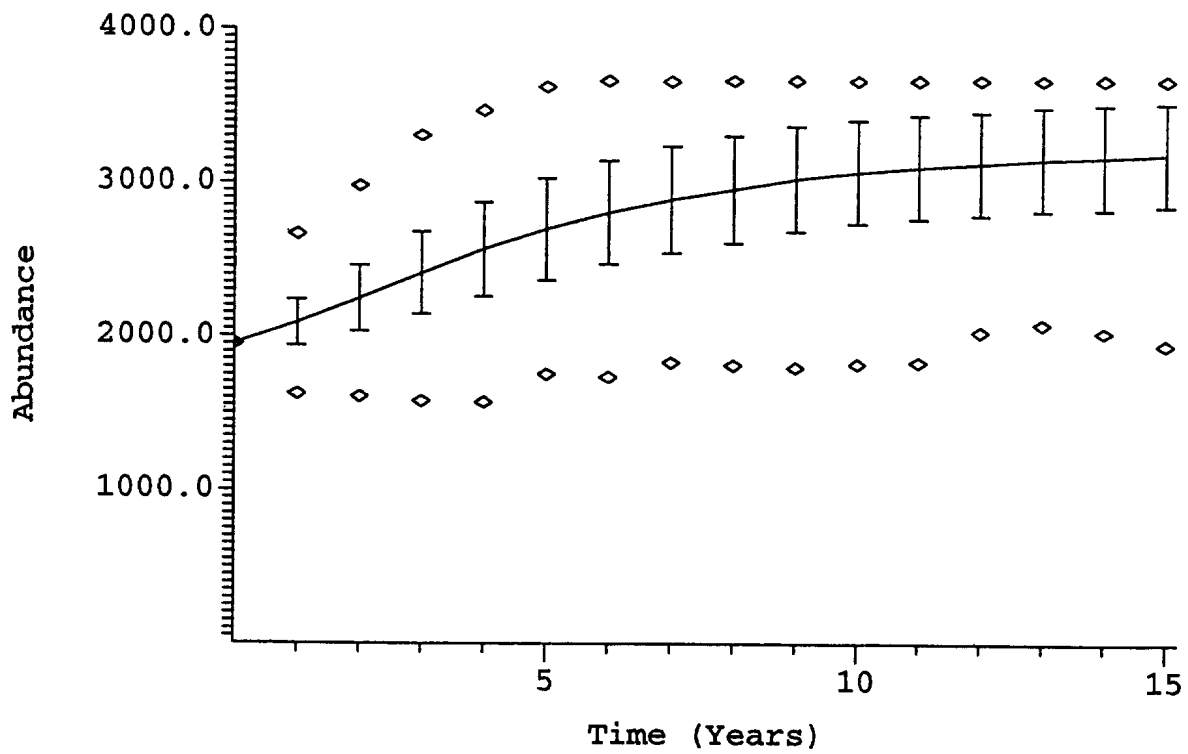
Trajectory summary

Figure D-9. Scenario 18: Recovery of snowy plovers assuming 1.3 chicks fledged per male in all subpopulations. Population trajectory for the metapopulation is shown for first 15 years of the scenario. Diamonds indicate maximum and minimum (400 simulations, total). Horizontal line indicates mean trajectory. Vertical lines connect mean +/- 1 standard deviation of outcome.